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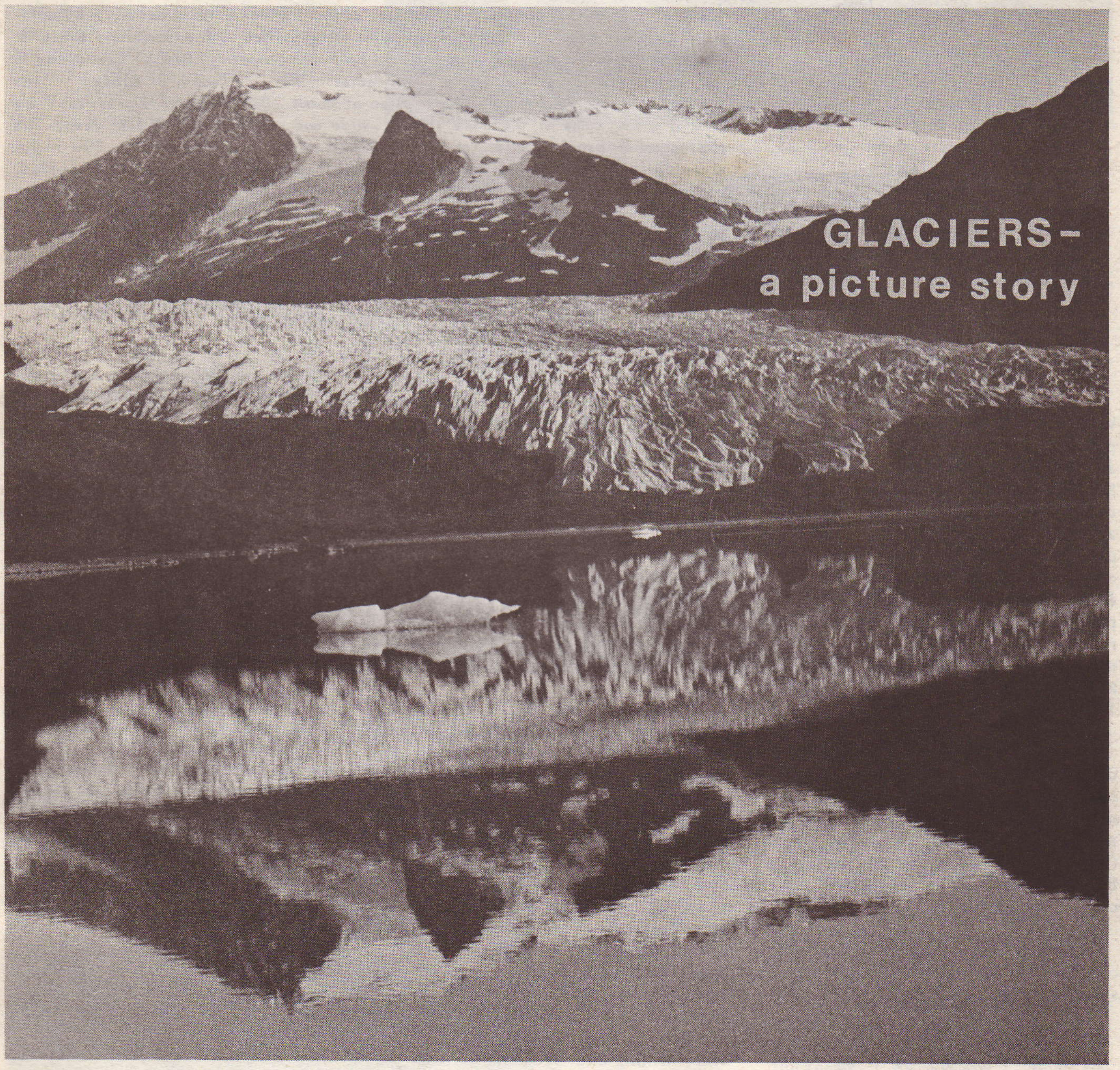
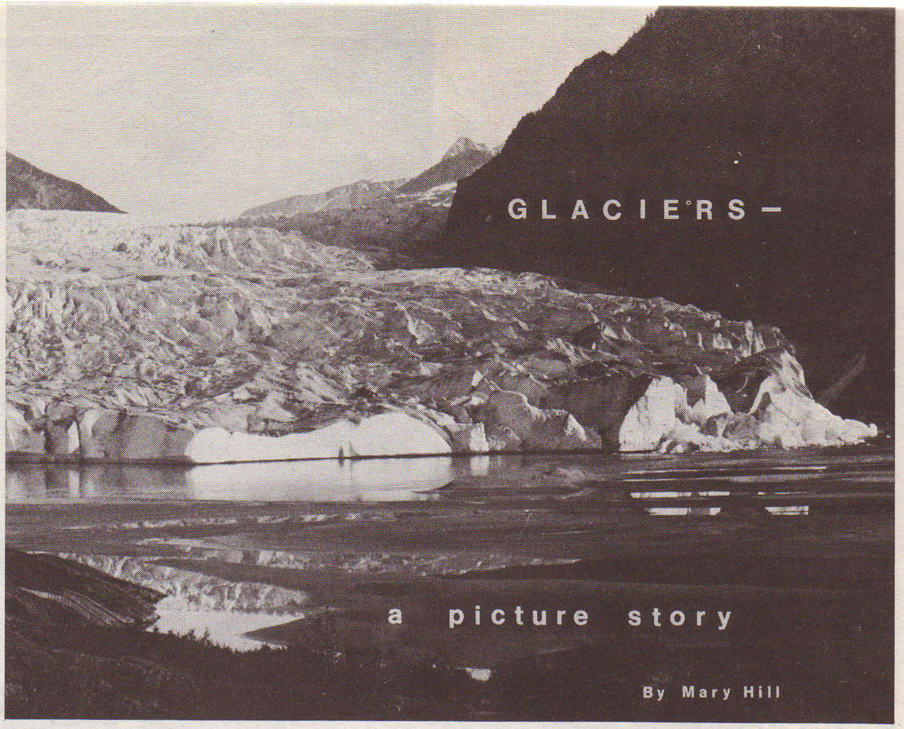
CALIFORNIA GEOLOGY

February 1974



Special thanks to the U.S. Geological Survey, Susan Moyer, Ernest Carter, and Ron Morgan for the illustrations that are the backbone of this article.



SUSAN MOYER

Figure 1.

What is a glacier?

A glacier is a mass of perennial ice on land that flows because of its own weight.

For giants like the Mendenhall Glacier, Juneau, Alaska, (figure 1) there seems little doubt that the word "glacier" applies. But there has not always been agreement that the small glaciers of California, like Dana Glacier (figure 2), are true glaciers. Some certainly are, as they are known to be moving.

U. S. GEOLOGICAL SURVEY, 1883

Figure 2.

Figure 3.

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How glaciers form

Glaciers form wherever the amount of moisture in snowfall added to the glacier exceeds the amount withdrawn by melting and evaporation (ablation). A long-term change is required for glaciers to be born; a few years of excessive snowfall do not make a glacier.

Today's glaciers, except for the ice caps near the poles, have accumulated in valleys, where snow could drift to great thicknesses. Boston, the largest single glacier in the North Cascades, Washington, shown in figure 3, is very tiny compared to Alaskan or Himalayan glaciers. Alaskan glaciers, lying in the far north, are large because the climate is generally colder toward the poles and because a great deal of moisture falls along the Pacific Coast. Northward, much of Alaska is iceless tundra, where snowfall is too small or it cannot accumulate on the ground. On the other hand, high peaks of northern Alaska, including Mount McKinley, harbor many large glaciers in valleys in their sides. Here the cold of the north combines with the cold of high altitude (20,000 feet) to provide a suitable glacial climate. Shown in figure 4 is Gulkana Glacier, Alaska, high in the Alaska Range.

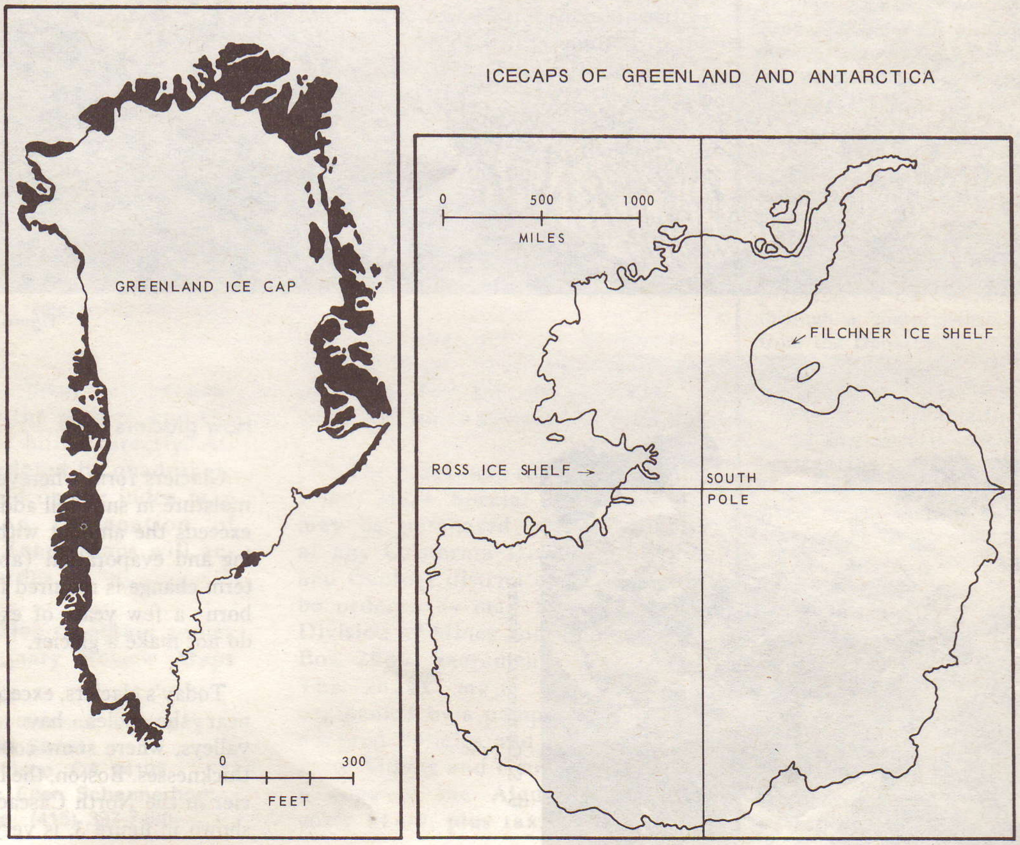
Himalayan glaciers, nowhere near the high latitudes, are relics of the ice age that have not yet melted, owing to their high altitude. (Mount Everest is 29,000 feet high.) Many Himalayan glaciers are now retreating.

Entire subcontinents are nearly covered by ice, even today. Shown in map 1 are the ice caps of Greenland and Antarctica, at the two poles. Ninety-nine percent of the world's glacial ice is stored in these great polar caps.

U. S. Geological Survey

Figure 4.

Map 1.



Ron Morgan

Glaciers of the U.S.

About 1100 glaciers hang in the mountains of the western states, and another 5000 cover much of Alaska. Glaciers in the lower 49 states, such as the group of small ones on Mt. Stuart, Washington, shown in figure 5, are mostly "cirque" glaciers. They occupy the area of the heads of former glaciers—spoon-shaped depressions carved by the ice.

Most of the approximately 80 glaciers in California lie in cirques. They are all very small; few are more than a mile in length. Other western U.S. glaciers are not much larger. In Washington, which claims nearly 800 glaciers, Emmons Glacier on Mt. Rainier (figure 6) is 5 miles long—all others are smaller.

Besides California and Washington, Wyoming, Montana, Oregon, and Colorado have recognized glaciers; Idaho, Nevada, and Utah have ice patches which might be considered glaciers.

If one were to amass the area of all of these glaciers (total of all Washington glaciers, for example, is 160 square miles), it could not cover the area of the nation's largest glacier, Bering, in Alaska. That mammoth is 127 miles long and covers an area of 2,250 square miles. About 3 percent, or 17,000 square miles, of the state of Alaska is covered by glaciers.

Figure 5.

U. S. Geological Survey

A glacier's budget

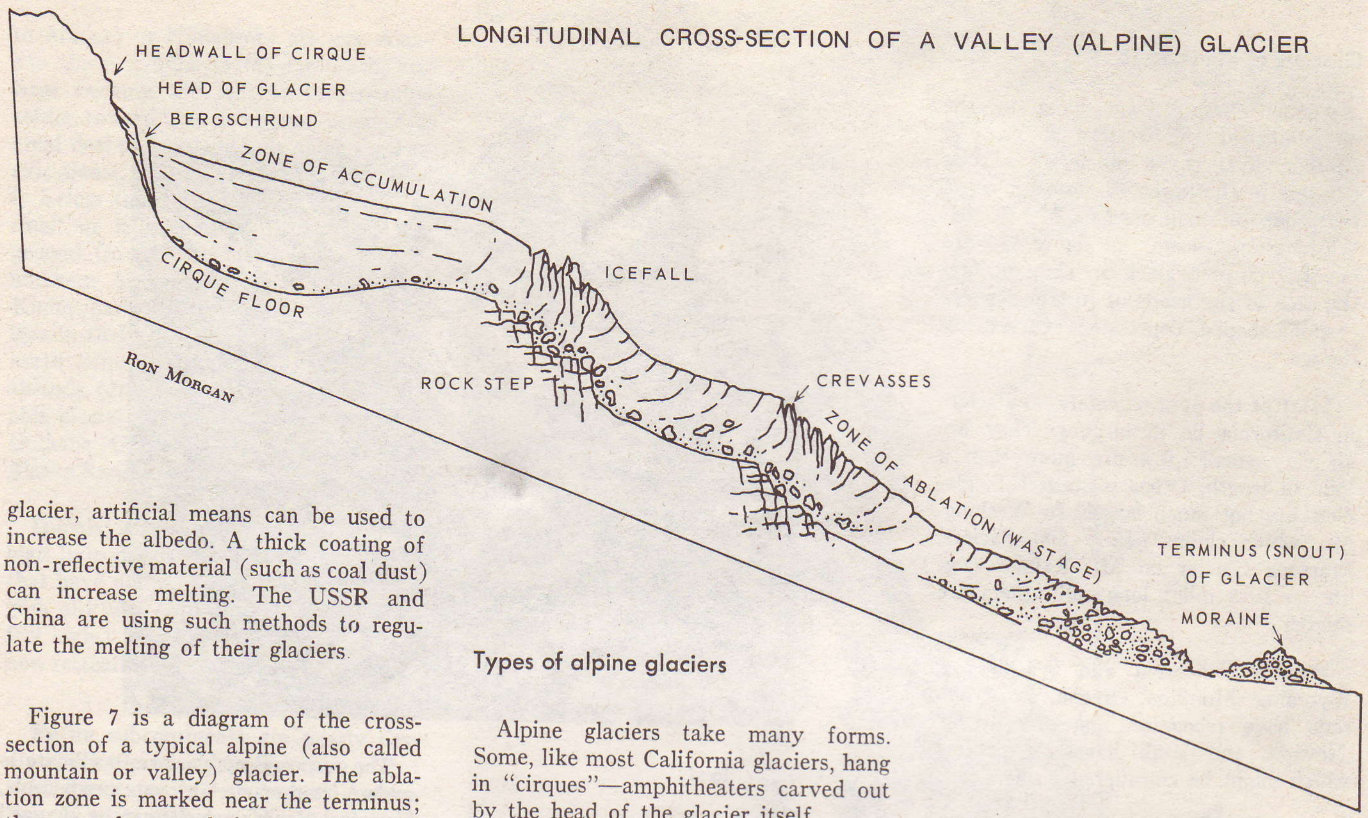
For all their massive size, glaciers are delicate, responding to changes in climate, although the response is not immediate. In general, glaciers have an annual budget; if "ablation" (the wasting of glaciers by melting and evaporation) exceeds accumulation, eventually the glacier must wane; if more snow accumulates to be changed to ice than is removed, the glacier will grow.

The response of glaciers to climate is seldom immediate or yet predictable. How fast the snow melts can be changed artificially, however. In nature, a heavy snowpack tends to insulate the snow and ice under it, preventing as great a runoff as in years of lesser snowpack. It is not only the snow overburden, but the glistening icy coating that reflects heat and prevents further melting. Such a coating is said to have a "high albedo" (reflectance). To prevent melting in a

Figure 6.

Ernest Carter

Figure 7.



glacier, artificial means can be used to increase the albedo. A thick coating of non-reflective material (such as coal dust) can increase melting. The USSR and China are using such methods to regulate the melting of their glaciers.

Figure 7 is a diagram of the cross-section of a typical alpine (also called mountain or valley) glacier. The ablation zone is marked near the terminus; the zone of accumulation near the head.

This glacier is a "cirque" glacier, as shown by the cirque floor marked near the head. Various other parts of the glacier, including the bergschrund (see page 30), icefall (see photo, page 39), crevasses (see page 38), and moraine (see page 31) are also indicated.

Types of alpine glaciers

Alpine glaciers take many forms. Some, like most California glaciers, hang in "cirques"—amphitheaters carved out by the head of the glacier itself.

Some are "hanging" glaciers, standing high on the mountain side, their termini suspended above the valley level. Figure 8 pictures a hanging glacier on Jack Mountain, Washington. Some glaciers commence from great ice fields, burying large areas of a mountain range (see page 23).

The terminus (also called "snout") of a glacier can end in a rock ridge or terminal moraine (see page 31); it can terminate in a glacial lake (see page 42) or at the sea ("tidewater" glaciers—see page 28).

A tongue of ice is what many of us think of when we think "glacier". Such a glacier is Wolverine, on the Kenai Peninsula, Alaska (figure 9).

Figure 8.

U. S. Geological Survey

How glaciers advance and retreat

Glaciers are not permanent in the mountain landscape. They wax and wane, depending upon the climate. Since 1883, when Israel Russell summarized knowledge of the glaciers of the U.S., most glaciers have been retreating, although the past decade has marked an increase in some.

Even in a stable climate, a glacier's energy may vary from time to time, and glaciers in different positions on the same mountain may react differently.

Shown in figure 10 is Chickamin Glacier on Dome Peak (8,935 feet), North Cascades, Washington. Glacier tongue at left is retreating; the terminus to the right is advancing.

U. S. Geological Survey

Figure 9.

U. S. Geological Survey

Figure 10.

Glaciers do not advance and retreat each year as the snowpack waxes or wanes. Rather, it may take many years of steady increase or decrease before a change is noticeable. The quantity of snowfall alone does not tell the story; how much water the snow contains, its density, and other factors are also critical. Scientists of the U.S. Geological Survey are shown sampling the wall of a pit on South Cascade Glacier, Washington in figure 11.

Figure 12 shows a well-marked "firn limit" or annual snowline on South Cascade Glacier, Washington. Toward the bottom of the glacier, the summer sun has melted the accumulated snow in the ablation zone, leaving the bare ice of the glacier visible. Icebergs floating in the meltwater lake at the front of the glacier testify to the near-freezing temperature of the lake. Snow persists on a glacier long after the surrounding rocks are clear, as the interruption of the snow surface by rocks and trees hastens melting.

The South Cascade Glacier in 1963 is depicted in figure 13, after a season of great melting due to a long clear summer. Most of the snow was removed from the glacier and older glacial ice was being

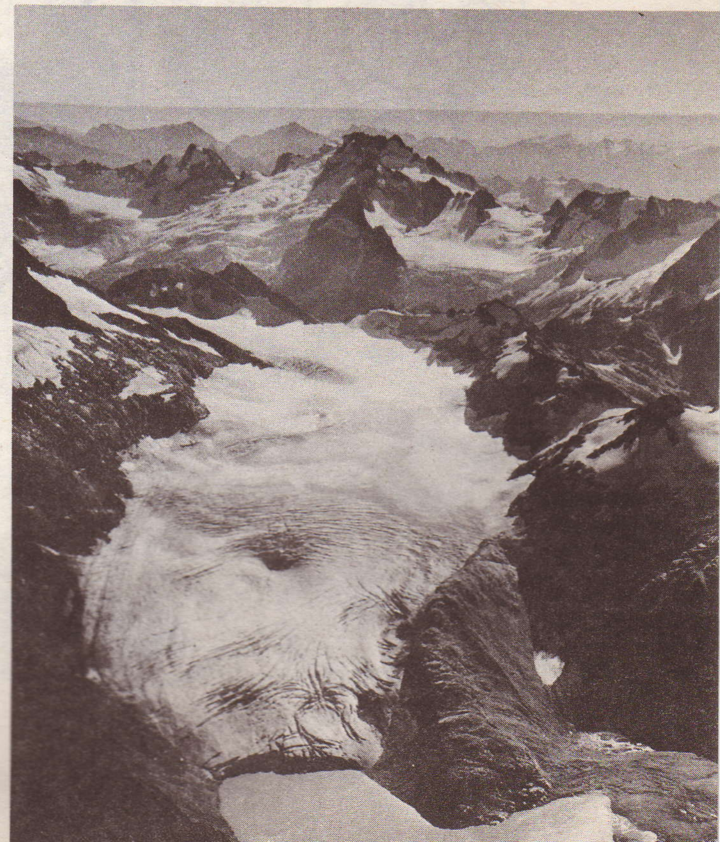
Figure 11.

U. S. Geological Survey

Figure 12.

U. S. Geological Survey

Figure 13.



U. S. Geological Survey

melted. Where melting exceeds accumulation steadily, the glacier retreats; when accumulation is greater, it advances.

In addition to melting and evaporation, "tidewater" glaciers that reach the sea are diminished by still another process of ablation known as "calving." As glacial ice is thrust forward in an active glacier, the seaward terminus is constantly eroded by the water and breaks off or "calves." Great masses of ice splash into the sea with resounding noise, there to become floating icebergs.

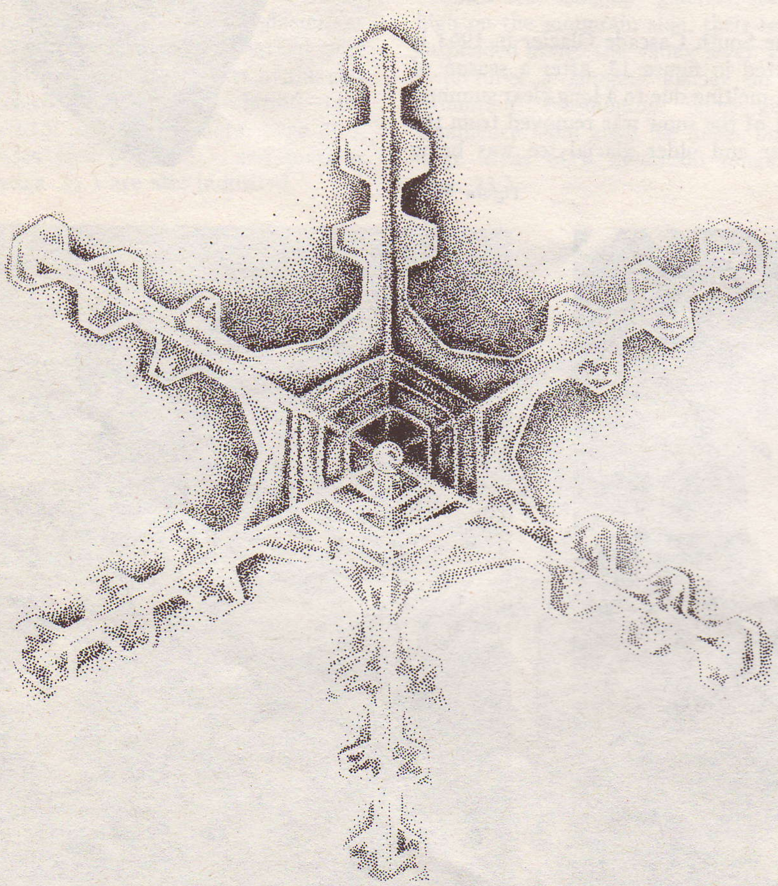
Valleys cut by tidewater glaciers become fjords when the ice melts, such as those at Glacier Bay, Alaska (figure 14).

SUSAN MOYER

Figure 14.

How snow becomes glacial ice

John Muir found it remarkable that, in excavating so large and deep a canyon as Yosemite, "Nature chose for a tool the tender snowflakes noiselessly falling through unnumbered centuries." †



RON MORGAN

Figure 15.

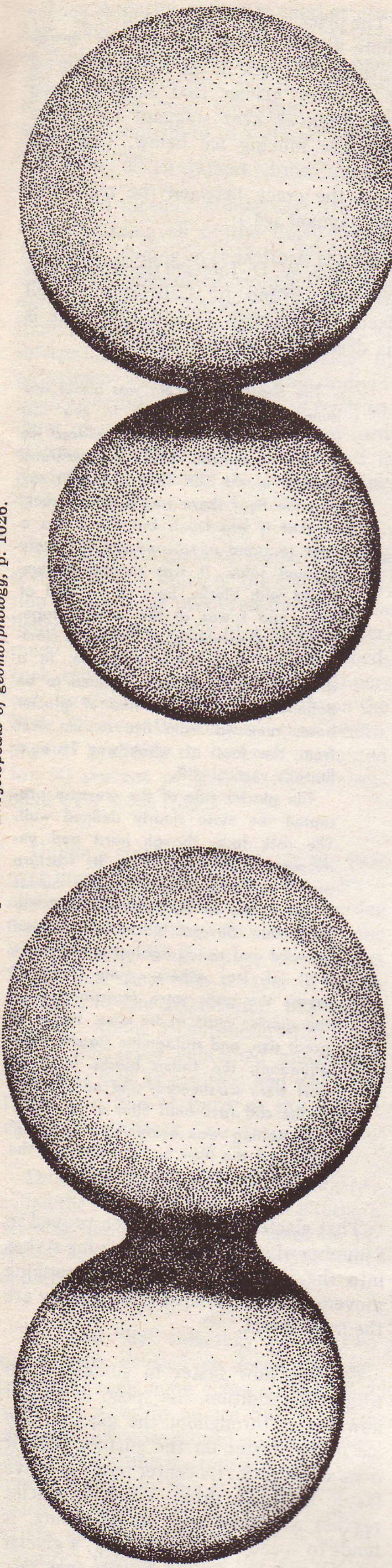
Nature's glacial tool begins, certainly, with the tender snowflake, but by the time it has been metamorphosed into glacial ice, it has become more tough than tender.

Snowflakes first change to tiny spheres, which become connected by minute necks that form where the spheres touch one another. Water vapor from the tiny balls migrates from the surface of the balls to the necks to form larger and larger necks, until the entire mass is sealed together. All of this takes place below the melting point, so that water is not necessarily present during the change; of course, if the temperature rises above freezing, so as to melt some of the snow, the liquid water will speed the process.

As it melds together, the snow-ice mass increases in weight and strength. Fresh snowflakes have a density of no more than a quarter of a gram per cubic centimeter —about a tenth the weight of water. Within weeks, the flakes become powder snow, about twice as dense and twice as strong; in months, old snow, doubling again in weight and strength; in years, they become "firn"—the material of

† *Mountains of California,* Doubleday and Company edition, 1961, p. 12.

Figure 16.



RON MORGAN after a photo in *Encyclopedia of geomorphology*, p. 1026.

which glaciers are made. In hundreds of years, they have consolidated into glacial ice, nine-tenths as heavy as water and a form of rock.

During this process, the original snowflakes have increased in weight 9 times, and in strength 500 times. They have changed in shape from dainty snow filigrees to dense crystals of glacial ice as much as 10 inches long.

Most of us would conjure up a mental picture of a snowflake much like the one shown in figure 15. True, the hexagonal shape is basic, but crystals are far from uniform. Viewed under the microscope, snowflakes are seen to be flat plates, long needles, dendrites, hollow prisms, or complexly irregular. The exact shape depends upon the flakes' origin and history. Charles and Nancy Knight, in a recent article entitled "Snow crystals,"* conclude that, based on the average weight of a snow crystal, the average amount of snow each year, the age of the Earth, and the water content of each snow crystal (10^{18} molecules), "it may very well be that there have never been two identical snow crystals."

Snowflakes, having become tiny ice spheres, begin to metamorphose into glacial ice. In figure 16, two spheres of ice half a millimeter in diameter are shown, held at a constant temperatures of –5° C. In *A*, they have just made contact; in *B*, 5 hours and 20 minutes later, a discernible neck has formed between the two. Eventually, if the cold continues, they and some of their fellows will become a single crystal of glacial ice.

Figure 17 is a drawing of crystals of glacier ice nearly a foot in length.

As glacial ice is compressed, it loses air that originally surrounded the snowflakes. Airless ice often appears more blue than less compacted ice; the blue is intensified where blue of the sky is reflected as well.

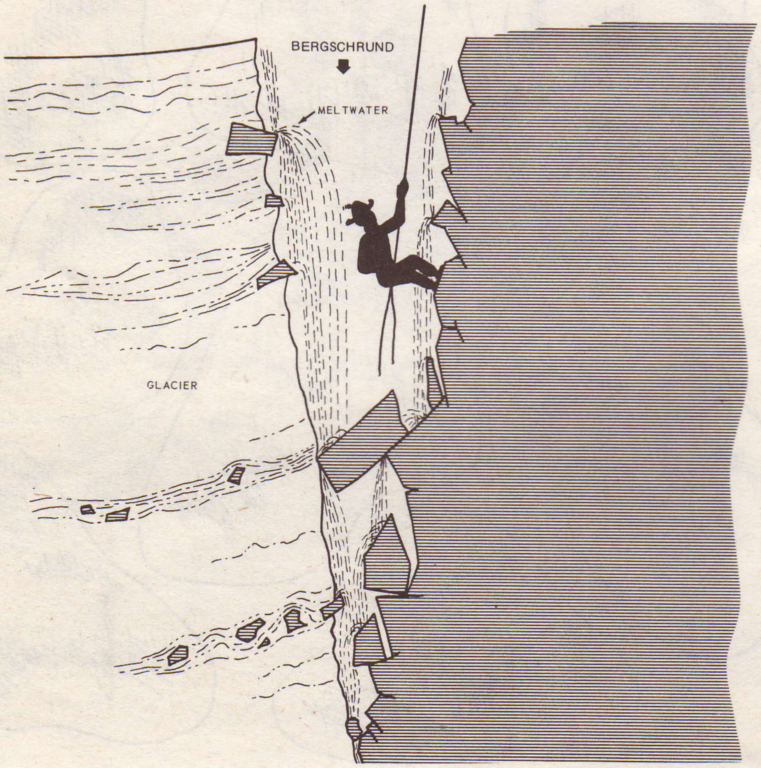
Figure 17.

RON MORGAN, after a photo by E. R. LaChappelle.

* *Scientific American*, vol. 228, no. 1, January, 1973. Pp. 100–107. Quotation is from p. 107.

J. A. FRASER

Figure 18.



RON MORGAN

Figure 19.

How glaciers move

The place at the head of a valley glacier where ice movement starts is the "bergschrund," a crack in the ice at the head of a valley glacier that separates the small area of near stagnant ice above from the moving ice below. (Another German word, *randkluft*, is used to name the crack between the rock wall and stagnant ice.)

In 1903, W. D. Johnson descended into the bergschrund of California's Lyell glacier (see figures 18 and 19). Here is his description of that adventure:

> The depth of descent was about one hundred and fifty feet. In the last twenty or thirty feet, rock replaced ice in the up-canyon wall. The schrund opened to the cliff foot. I cannot say that the floor there was of sound rock, or that it was level; but there was a floor to stand upon, and not a steeply inclined talus. It was somewhat cumbered with blocks, both of ice and of rock; and I was at the disadvantage, for close observation, of having to clamber over these, with a candle, in a dripping rain, but there seemed to be definitely presented a line of glacier base, removed from five to ten feet from the foot of what was here a literally vertical cliff.
>
> The glacier side of the crevasse presented the more clearly defined wall. The rock face, though hard and undecayed, was much riven, its fracture planes outlining sharply angular masses in all stages of displacement and dislodgement. Several blocks were tipped forward and rested against the opposite wall of ice; others, quite removed across the gap, were incorporated in the glacier mass at its base. Icicles of great size, and stalagmitic masses, were abundant; the fallen blocks in large part were ice-sheeted; and open seams in the cliff face held films of this clear ice. Melting was everywhere in progress, and the films or thin plates in the seams were easily removable. ✱

That glaciers move has been proved in a number of ways, of which driving stakes into the ice surface and photographing movement by time-lapse photography are the most direct.

Glaciers flow faster in summer than winter; in addition, the speed of glacial flow varies throughout the glacier. The ice moves faster on the surface than it does at bedrock; its center tends to move faster than its sides. When a glacier reaches a narrow spot in its valley, it tends to speed up. Occasionally, a glacier may speed forward at a very fast rate (see photos of surging glaciers, page 37).

✱ "The profile of maturity in alpine glacial erosion," *Journal of Geology*, vol. 12, pp. 569–578, 1904.

How a glacier moves is another question. Five possible mechanisms by which a glacier might move are shown in figure 20. Of these, the first and the last probably are the most important, although all might contribute to a glacier's movement at times.

In cold glaciers (those that are well below freezing all of the time) and in ice sheets, sliding over bedrock probably does not happen often enough, if ever, to account for the glacier's motion. Most likely, these glaciers move principally by intragranular readjustment—gliding by adjustment of molecules within individual ice crystals. Since continued readjustment of ice crystals would tend to form elongated crystals unlike any found in glaciers, it is assumed that, after gliding, each crystal is reformed.

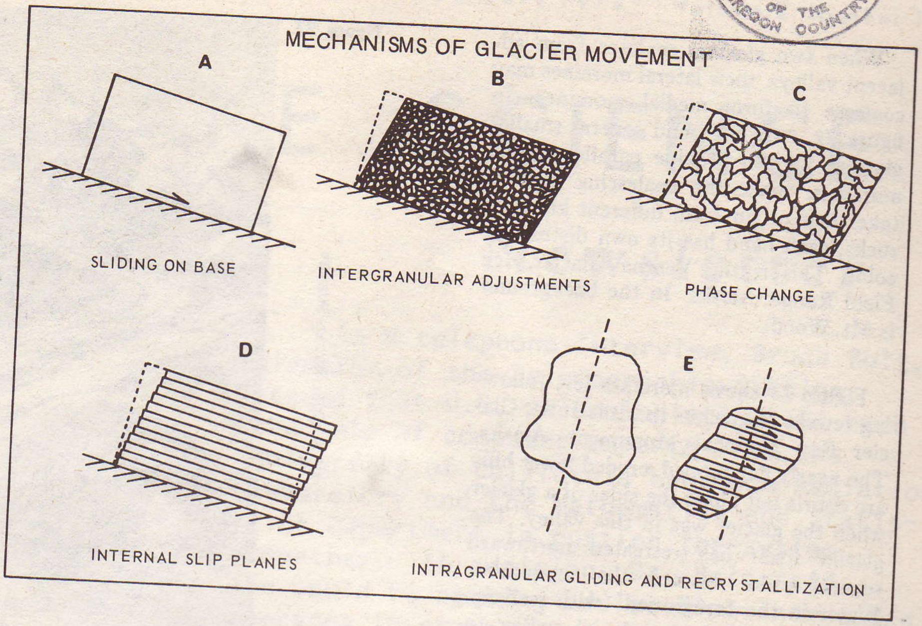
In temperate glaciers (those near the melting point), much of the glacier's motion seems to be produced by sliding on bedrock. In one study of a Swiss glacier, made by tunneling into the ice near bedrock, movement was shown to be 90 percent by sliding. In a similar study on the Blue Glacier, Washington (see photo, page 37), sliding on bedrock accounted for 90 percent of that glacier's movement over steep slopes.

Unlike a stream of water, ice can pass over many obstacles. How it does this—obviously ice pressure is a governing factor—is intriguing. In studying the Blue Glacier, Washington, glaciologists found that there was a layer of ice at the base of the glacier that was unlike the rest. About 3 centimeters thick, the ice in this layer contained much rock debris, as well as cavities, and what was probably a film of water at the contact of ice and bedrock.

This suggests that it is in this layer—called the regelation layer—that alternate freezing and thawing takes place, in response to pressure. It is along this layer, apparently, that the glacier slips.

To show that this may be so, two glaciologists devised an interesting experiment: they hung cubes of rock and metal on wires in an ice block. Under pressure, the cubes moved slowly through the ice by melting in front and refreezing behind. Probably this is the manner in which ice flows over obstacles: melting on the upstream side (due to increased pressure), flowing around the obstacle as water, and refreezing on the lee side.

Figure 20.



Ron Morgan

Moraines

As glaciers move, they heap up rock debris ahead of them and to their sides in heaps called moraines. At the terminus of a glacier, a terminal moraine marks advances and retreats. Most of today's glaciers in California have simple, though perhaps multiple, moraines. The single terminal moraine of Mammoth Glacier, Wind River Range, Wyoming (source of the Green River) shown in figure 21, is similar to the small moraines of California's tiny glaciers.

Lateral moraines are sharp crested ridges of rubble along the edge of a valley glacier in the lower, ablation zone below the firn line. As a glacier retreats, a paired set is left along the valley walls.

U. S. Geological Survey

Figure 21.

When two glaciers coalesce from adjacent valleys, their lateral moraines may coalesce to form medial moraines. In figure 22, two large and several smaller glaciers join to provide parallel medial moraines. Since the coalescing glaciers take their origin from different kinds of rocks, each band has its own distinctive color. This is the Yentna Glacier, Ice Field Range, Alaska. In the background is Mt. Wood.

Figure 23 shows moraines left following retreat of glaciers in Muir Inlet, Glacier Bay National Monument, Alaska. The nearly flat-topped, eroded lower hills are debris left along the sides of a glacier when the glacier was in this valley. The glacier itself has retreated northward several miles toward the mountains. Water in the foreground (with icebergs afloat) has filled the glacial valley to form a fjord.

Figure 22.

U. S. Geological Survey

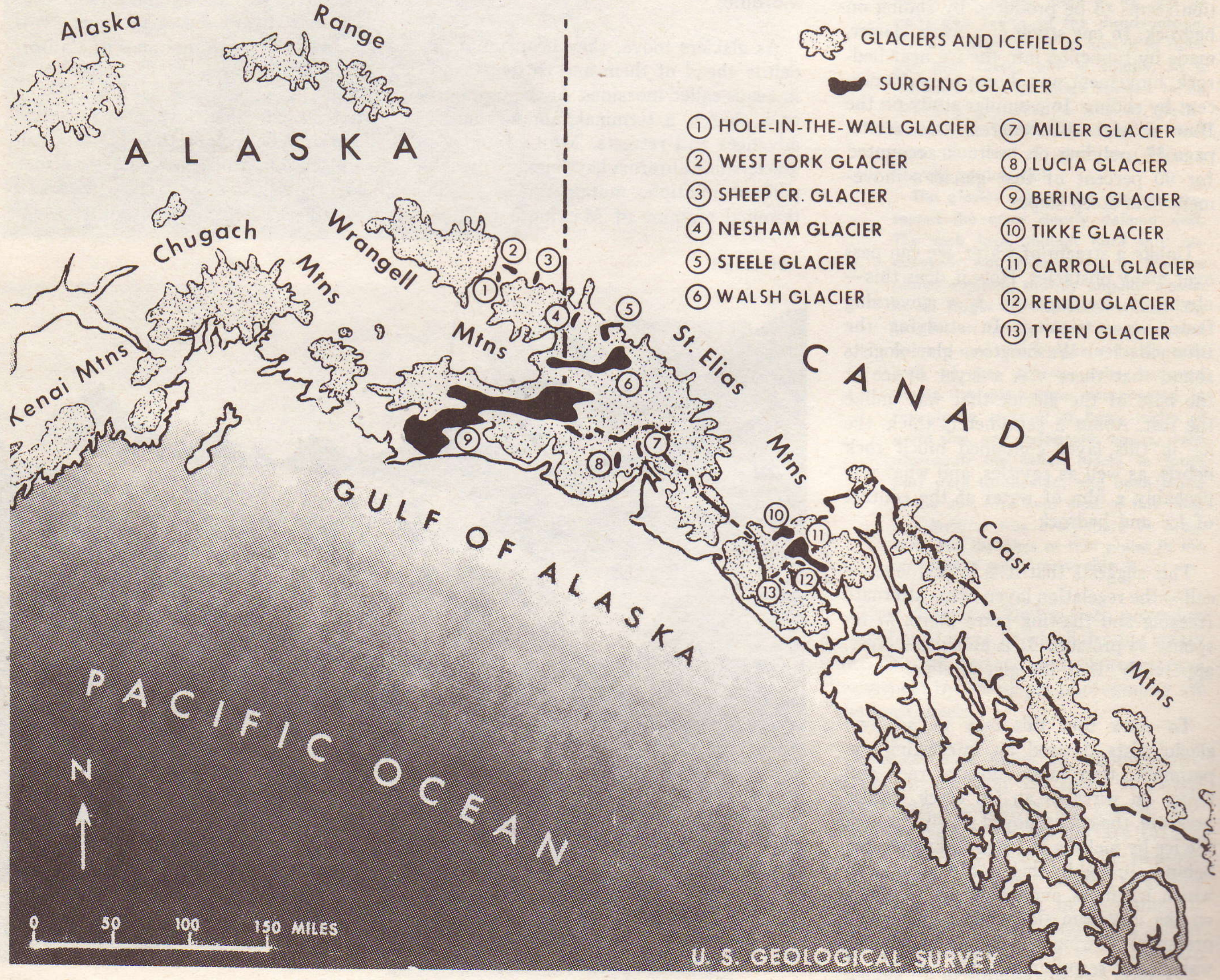
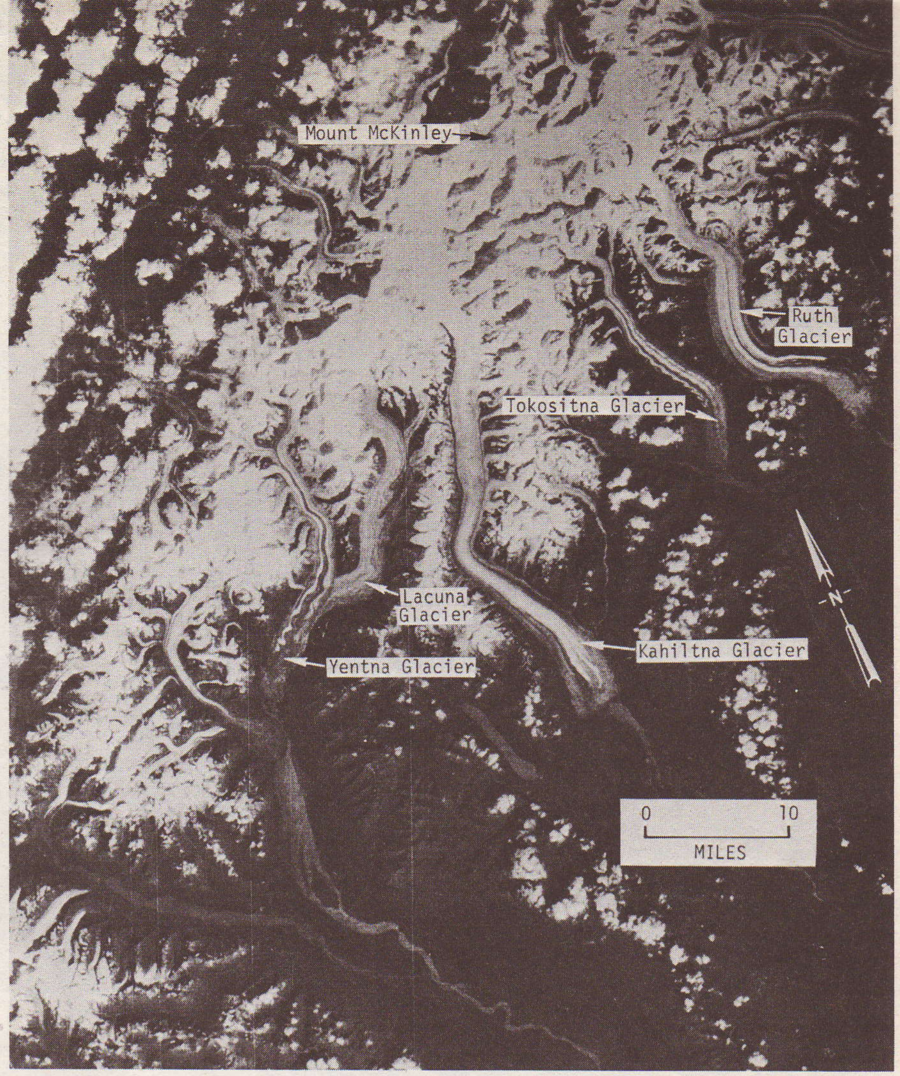


Figure 23.

Figure 24.



U. S. Geological Survey

Surging glaciers

Some glaciers show, not straight medial moraines, but twisted, contorted ones "reminiscent of chocolate marble cake", particularly in their lower reaches. Such contorted bands are the result of glacial "surges"—sudden rushes of movement by the glacier.

Not all glaciers surge; those that do seem to be in the same general areas, although all glaciers in that area do not surge, and those that do, do not move at the same time. Size seems to have nothing to do with it; small or large may surge. Study of more than 200 surging glaciers has given this picture of a surge:

After a considerable time (15 to 100 years), a wave of ice from the upper part of a glacier begins to move downhill. The surface of the glacial ice is broken up by the advancing wave, moving ice as much as 10 percent of the length of the glacier in a single year. There is no overall increase in glacial volume; the terminus of the glacier is increased at the expense of the upper parts. The lower, previously stagnant ice is thickened and moves forward. Surges rarely last more than 3 years, but the same glacier may surge again after an interval.

Glaciers have been known to surge as rapidly as 4 feet per hour.

Some "galloping"—surging—glaciers in Alaska are shown in the ERTS photo in figure 24. Study of such glaciers by satellite may explain why glaciers surge, or at least, when they may surge, so as to warn those in the path of glaciers or glacial floods.

Moraines of the Yentna Glacier (see also page 31) have moved more than 6000 feet down valley since 1973.

Figure 25.

U. S. Geological Survey

On June 20, 1973, a huge lake dammed up by the advancing Bear Glacier, Tadzhik Republic, near the Chinese and Afghanistan borders, U.S.S.R., broke through its ice barrier. A flash flood, carrying boulders and ice, roared through the Vanch Valley, destroying considerable property, including electric lines and highways. Although the valley has a population of 10,000 people, Russian geologists had predicted the flood 2 months in advance, so that people and livestock could be evacuated, and bridges, barriers, and protective dikes constructed.

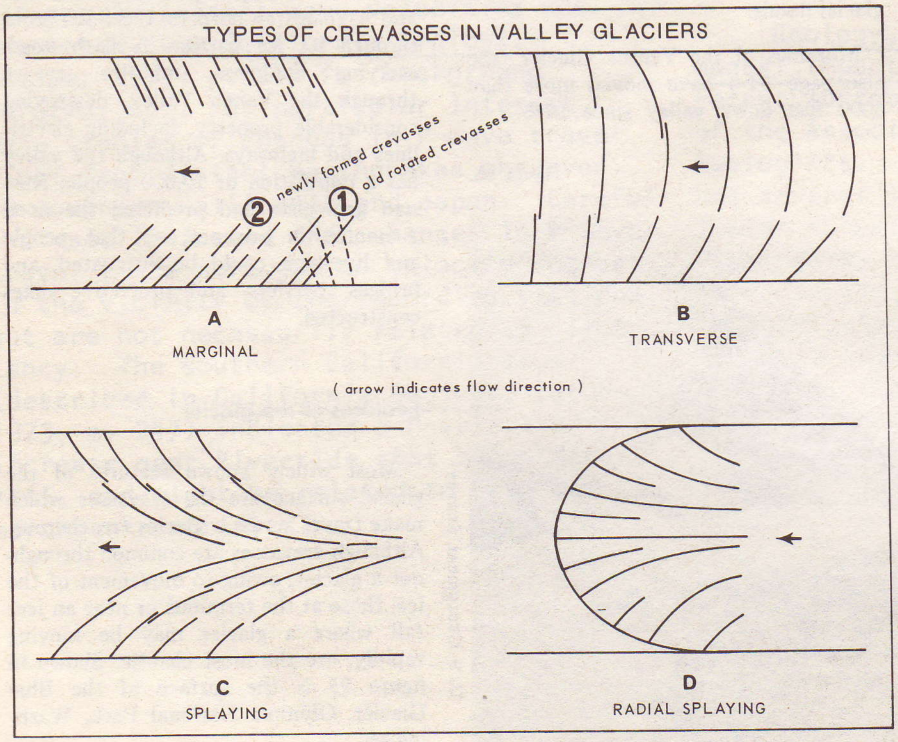
Features of the glacier

Most widely known features of the glacial surface are the crevasses which make travel across a glacier treacherous. Although crevasses are common throughout a glacier, owing to movement of the ice, those at the terminus or near an icefall where a glacier may be moving rapidly, are the most chaotic. Shown in figure 25 is the surface of the Blue Glacier, Olympic National Park, Washington.

U. S. Geological Survey

Figure 26.

Figure 27.



After Sharp, 1960.

Figure 26 is an air view of crevasse patterns on the Gakona Glacier, Alaska, after a rapid glacial surge. Individual blocks, called "seracs", are very little melted and still show their original shape. Glacier surfaces like this are nearly impossible to traverse on foot.

Crevasses and crevasse patterns, some of the hallmarks of a glacier, are of several kinds:

Chevron crevasses (upper left), forming along the edges of glaciers (old ones may be twisted).

Transverse crevasses, convex upstream (upper right).

Splaying crevasses (lower left), commencing parallel to the length of a glacier, but curving toward the sides.

Radial splaying crevasses, lower right, characteristic of the glacier's terminus (snout).

The direction of ice pressure is indicated in figure 27 by arrows.

Ice falls and ogives

Ice falls or ice cascades may separate the upper ice plateaus where ice and snow accumulates from the lower areas (ablation zones) where it dissipates.

The ice fall of Margerie Glacier, Glacier Bay National Monument, Fairweather Range, Alaska, is shown in figure 28. Mount Quincy Adams and Mount Fairweather (15,300 feet in elevation—highest of the Fairweather Range)– in background.

Surface of a glacier showing light and dark banding called "ogives" (figure 29). The white bands are light, bubbly ice; the dark bands have more heavier, bluer, bubble-free ice. Ogives form below ice falls: the dark layer represents that part of the glacier that spent the summer descending the ice fall. As it descended, ice crystals grew by melting and freezing, adding to themselves dirt from the ice surface. In winter, the ice fall remained frozen; ice crystals remained small, and the ice surface was protected by a mantle of snow, so that the winter accumulation at the ice fall foot reconsolidated into cold, white, bubbly ice.

Figure 28.

U. S. Geological Survey

Figure 29.

Susan Moyer

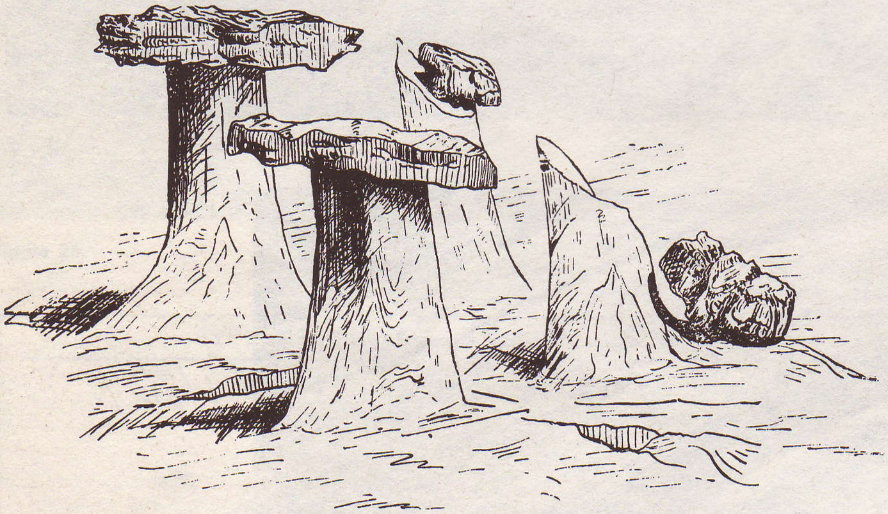
Figure 30.

After the bands are formed, the white ones have greater reflectance (albedo), and therefore stand higher than the darker, dirtier, more easily melted blue-ice bands. Not only does the blue ice absorb more heat, and therefore melt faster, but it also collects meltwater as it continues to be lower than the white bands. As it collects meltwater, it also collects more dirt, accentuating the color difference, and emphasizing the pattern.

Other accumulation layers of dust, marking the summer's "dirt", are shown on the northern side of Paradise Glacier, Mt. Rainier, in figure 30. Wet winters, cold winters, dry summers—all leave their marks as layers of dust, particularly in glaciers on volcanic mountains. To the right is the Beehive Glacier, its bergschrund sharply marked by shadow.


ERNEST CARTER

Figure 31.

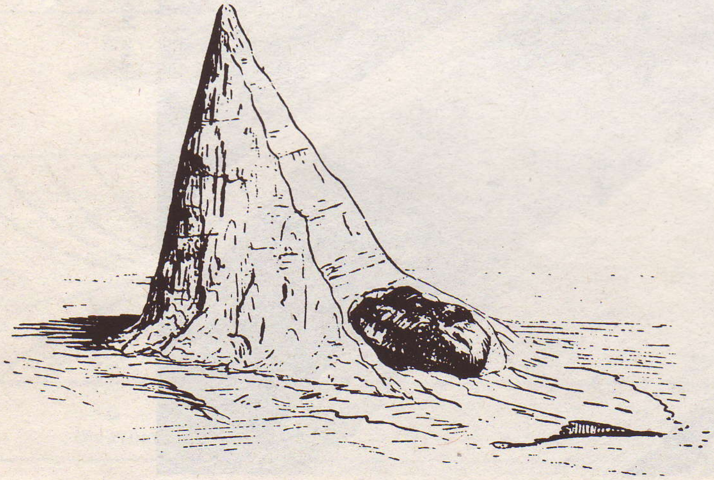

ISRAEL C. RUSSELL

Ice tables

At times, the dirt and debris accumulated on the surface of the glacial ice is thick enough to insulate the ice of the ablation zone from normal melting. Areas so insulated may stand above the rest of the ice for one season, or many seasons.

At times, one large rock being carried on the ice surface may protect the ice beneath it so as to remain as a pedestal above the glacier surface. Known as "glacial tables", they are common in the melting zone of a glacier. The sketch shown in figure 31 was made by Israel C. Russell in 1883, and shows glacial tables of the Parker Glacier, Sierra Nevada, California.

Figure 32.


ISRAEL C. RUSSELL

Ice ships

"Ice ships"—so named for their resemblance to sailboats—are common in high altitude, low latitude glaciers, where they may start as glacial tables that have lost their protecting rocks. They were first named from their appearance on Khumbu Glacier, Himalayas, where they were quite large. Very small ice ships, called "ice pyramids" by early explorers, were seen on California glaciers in the 1880 s. Shown in figure 32 is one sketched from the Mount Lyell Glacier in 1883.

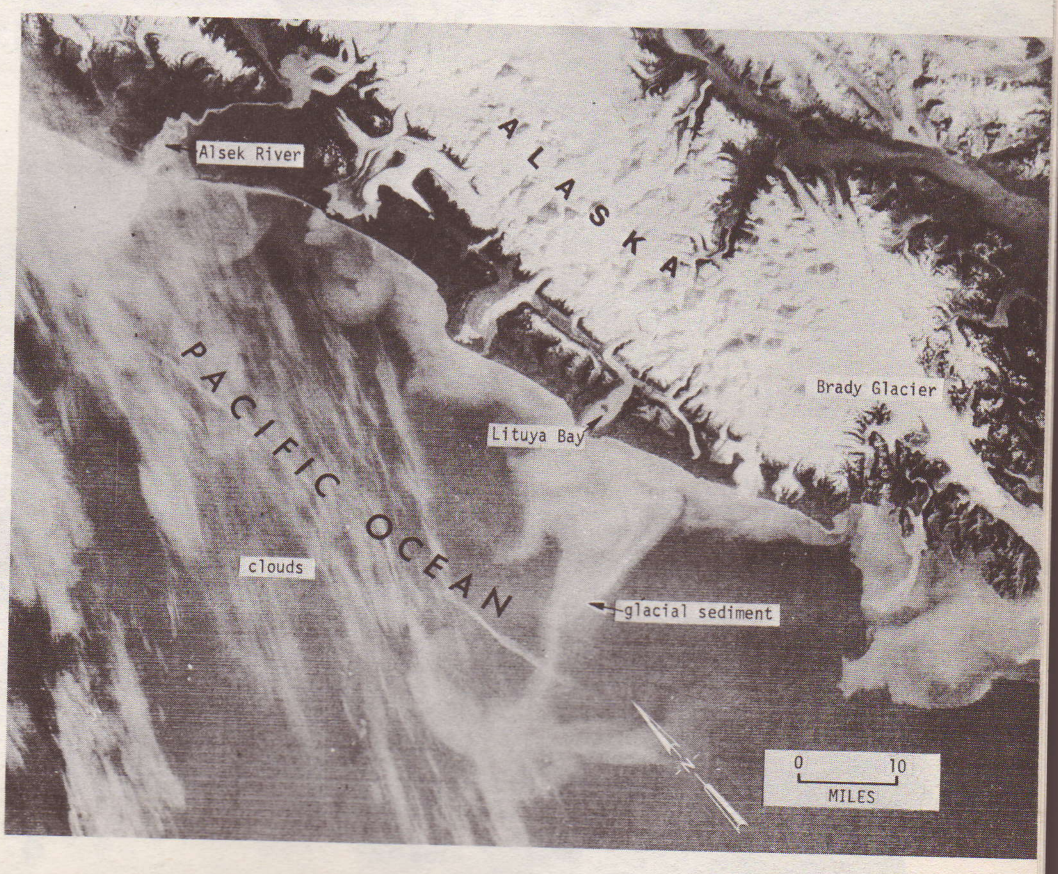
Figure 33.

SUSAN MOYER

Sun cusps

Sun cusps in ice on Brady Glacier, Fairweather Range, Alaska are shown in figure 33. Ablating of a glacier rarely proceeds uniformly. Irregularities in the ice, rocks, or dust on the surface, cloud or mountain shadows, angle of sun—all of these contribute to uneven water loss. Some irregularities form when warm sunny days cause the high or clear parts in the ice to sublimate, while the lower more shadowed parts, melt. About $7\frac{1}{2}$ times as much heat is required for sublimation.

Figure 34.



U. S. GEOLOGICAL SURVEY

Glacial flour

Only rarely can one see today's California glaciers in the process of changing the landscape. In Alaska, where some 5000 valley glaciers are constantly at work, the products of their erosive activity are constantly visible. Where waters of a glacially laden stream meet another body of water, a very sharp line may mark the interface. This glacial "flour"—actually finely ground rock—is generally tan in color.

The glacial plumes shown in figure 34 are from tidewater glaciers of Glacier Bay, Alaska. They extend more than 30 miles into the Pacific Ocean. The view is from Earth Resources Technology Satellite (ERTS).

Jökulhlaups

Glacier outburst floods take place when the drainage channels within a glacier become stopped up. The overall channel system resembles the branches of a tree, gradually coalescing to form one or more trunks carrying a large amount of water and rock debris. Why the channels should become stopped is not entirely clear; probably movement of the ice serves to dam the water, storing it in or adjacent to the glacier. Later, this water may be released suddenly as an outburst flood or, to use the Icelandic term, "jökulhlaup"(yo'kool-loup). In Iceland, jökulhlaups are sometimes caused by volcanic eruptions when glacial ice is suddenly melted by a lava flow.

Such floods can be quite large (up to 70,000 cubic feet/second in the Nisqually River at Mount Rainier in 1955) or even catastrophic where glaciers are larger.

One of the largest floods on record is the 1922 jökulhlaup from Grimsvotu, Iceland, which discharged about 1.7 cubic miles of water in a 4-day period, producing a flood which was estimated to reach about 2 million cubic feet per second of water at its peak. This is 10 times the discharge rate of the Mississippi River. Huge boulders can be carried in the flood. Four years earlier, in 1918, a Grimsvotu jökulhlaup moved one rock that was 400 cubic meters (roughly 400 cubic yards) in size a distance of 14 kilometers (8½ miles).

The world renowned breakout of Lake George, 50 miles east of Anchorage, Alaska, is a familiar example of a jokulhlaup. Most summers, ice-dammed Lake George (center of figure 35) empties itself through a narrow gorge between Knik Glacier (left foreground) and Mount Palmer (at right) into the Knik River.

In a normal year, the water in the basins is sealed effectively from entering the Knik River Valley by a mass of ice 250 feet thick. But as meltwater continues to flow into the lake, it overflows the ice dam and cuts a channel between Knik Glacier and Mt. Palmer. At the height of the emptying— 2 or 3 days after the initial breakout— the rapidly flowing water cuts a gorge 100 to 400 feet wide, extending to the base of the glacier. Overhanging sections of ice, some as long as a city block, and as tall as a 15-story building, fall with thunderous reverberation into the widening gorge. After 12 to 15 days, Lake George has emptied itself, and once again, there are three shallow basins containing water. When winter comes, the advancing front of Knik Glacier rebuilds the ice barrier.

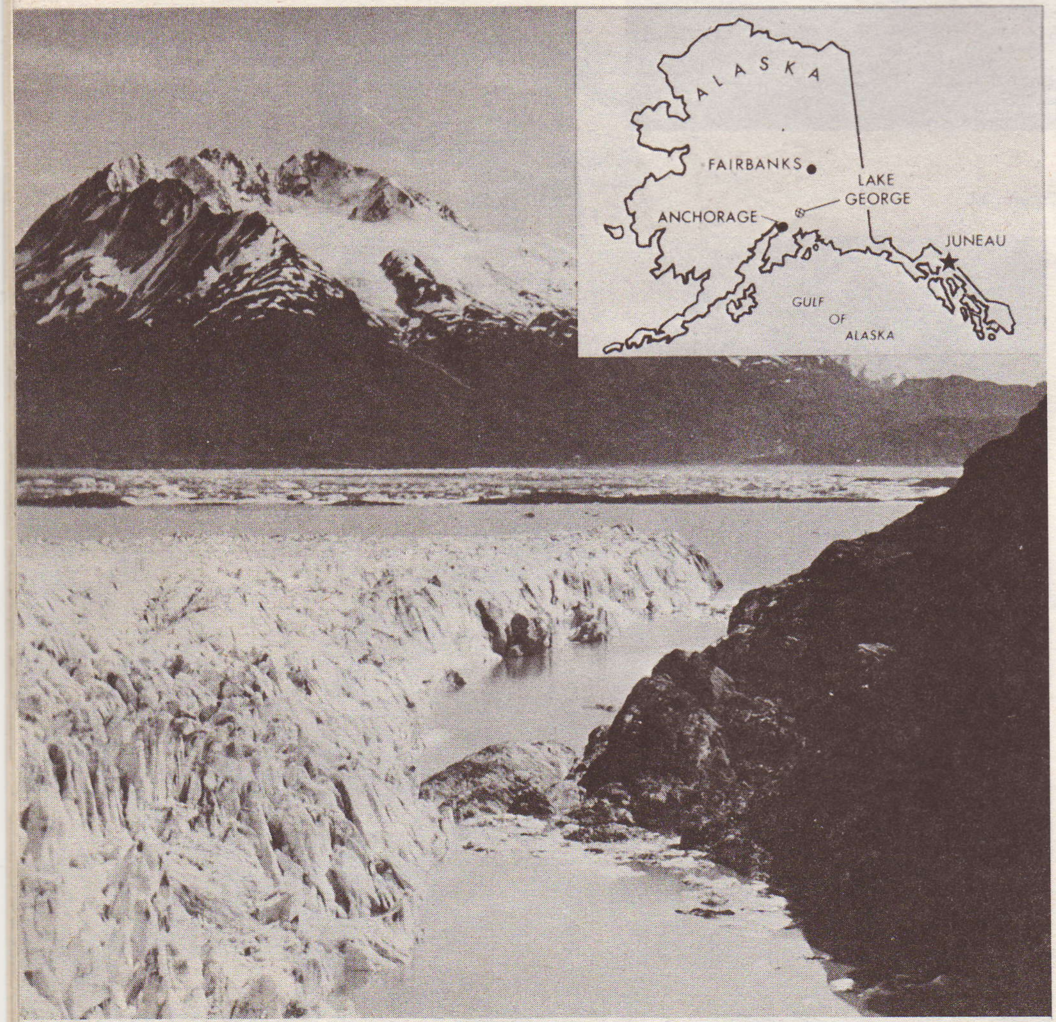


Figure 35.

The flood resulting from the breakout has sometimes damaged or destroyed bridges and highways, and plagued residents along the Knik River and the lower Matanuska Valley. However, even though future breakouts may continue to be a threat to people living along the Knik River, they can now be warned in advance of the oncoming flood because of studies that have been made of the breakout pattern in recent years.

Lake George, like all ice-dammed lakes, is a phenomenon not likely to last very long—at least not long in terms of geologic time. As demonstrated in recent years, the balance between the advance of Knik Glacier and the accumulation of a large lake behind the ice dam is a delicate one. Either of two events is likely to upset the balance: one, if the climate warms appreciably, or if yearly snowfall decreases, Knik Glacier will retreat farther up valley, and the ice dam will not form. Second, if the climate becomes colder or much more snow accumulates yearly, the glacial ice may advance sufficiently to fill most or all the basin that contains Lake George. If this happens, the accumulation of meltwater would be insignificant.

The age of Lake George is unknown, but it may be in a late stage of its existence.

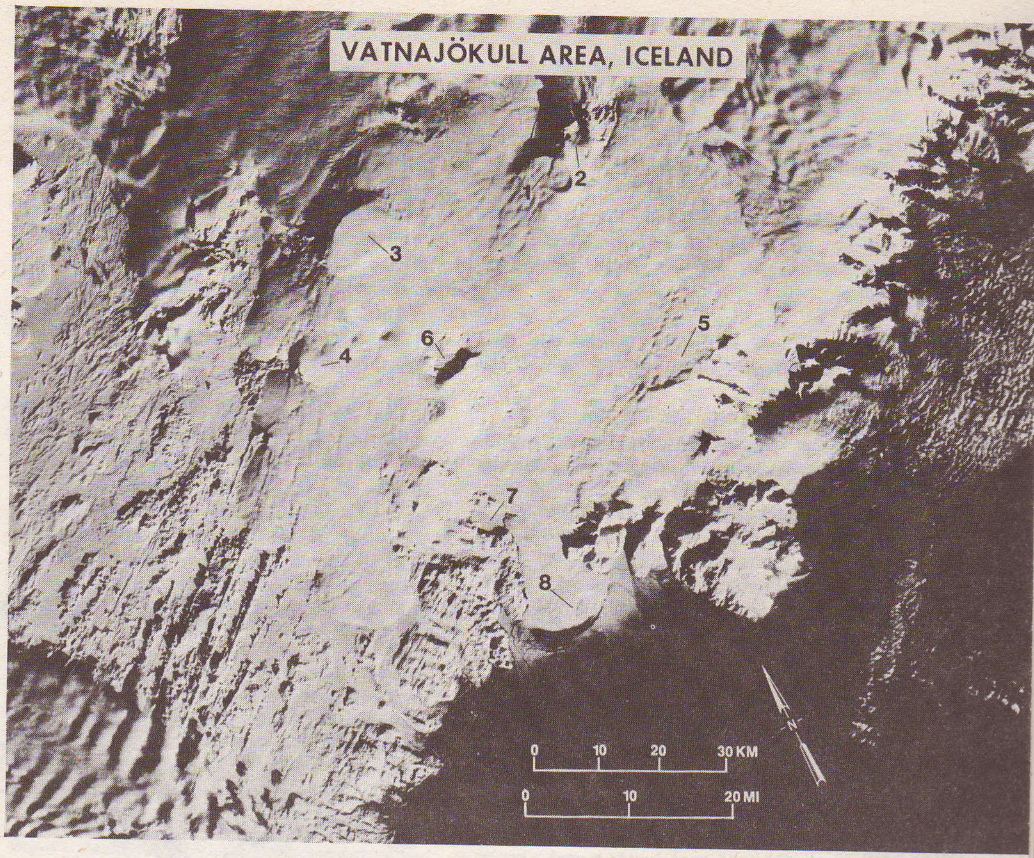
Figure 36.

Iceland from space

Figure 36 is a NASA Earth Resources Technology Satellite (ERTS-1) image of snow-covered Vatnajökull area, Iceland, showing a number of volcanologic and glaciologic features within the Vatnajökull ice cap, including subglacial volcanic features (no. 1–5), lakes that have caused sudden catastrophic floods in the past (no. 6–7), and the snout of a prominent glacier (no. 8).

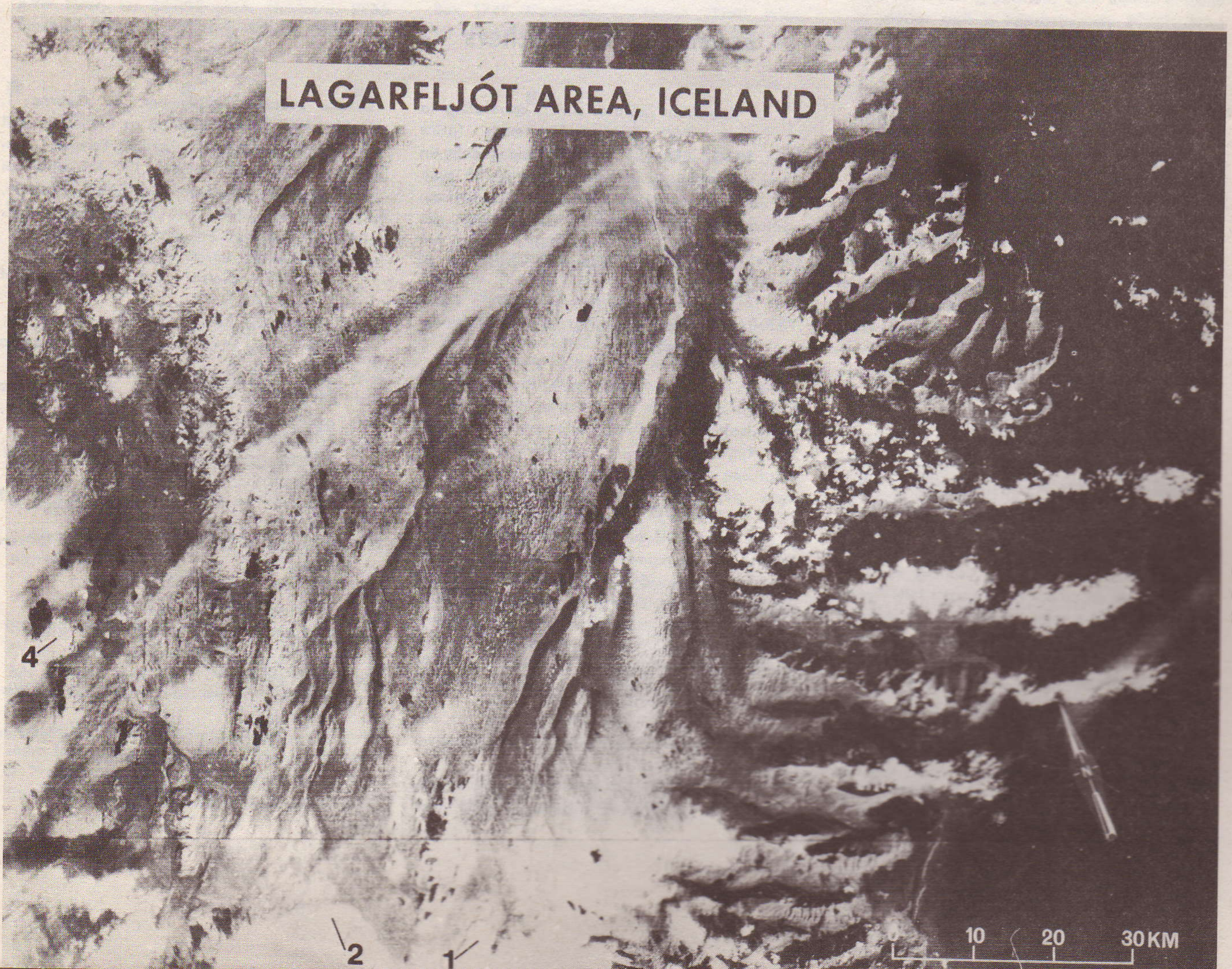
In figure 37, NASA Earth Resources Technology Satellite (ERTS-1) image of northeast Iceland reveals "surging" glaciers (no. 1 and 2); the 1961 volcanic lava flow (no. 3); and the 5,500-foot table mountain of Herdubreid (no. 4).

About 75 percent of Iceland's area is covered by glaciers, lakes, lava, sand, or is otherwise unproductive, leaving only about 390 square miles for agricultural cultivation and about 8,900 square miles for animal grazing. Because of its importance to the Iceland economy, much of the scientific effort is necessarily directed at an understanding of the environment.



U. S. Geological Survey

Figure 37.



U. S. Geological Survey

Additional Reading

Dyson, James L. 1962. *The world of ice.* Alfred A. Knopf, New York. 292 p.

Embleton, Clifford, and King, Cuchlaine A. M. 1968. *Glacial and periglacial geomorphology.* St. Martin's Press, New York. 608 p.

Flint, Richard F. 1971. *Glacial and Quaternary geology.* John Wiley & Sons, New York. 553 p.

Fristrup, Børge. 1966. *The Greenland ice cap.* University of Washington Press, Seattle. 312 p. (The history of exploration and nature of the Greenland ice cap.)

Harrison, A. E. 1960. *Exploring glaciers with a camera.* Sierra Club, San Francisco. 71 p.

Post, Austin, and LaChapelle, Edward R. 1971. *Glacier ice.* University of Washington Press, Seattle. 110 p.

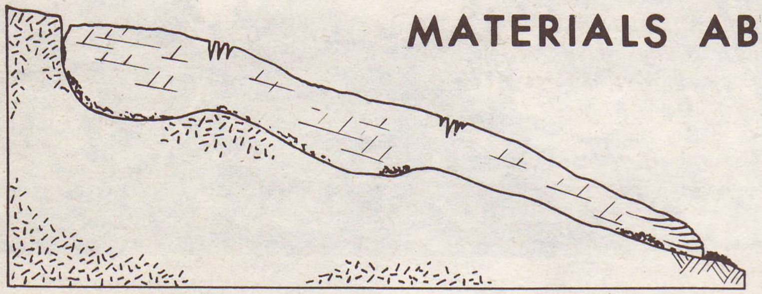
San Ahlmann, H. W. 1953. *Glacier variations and climatic fluctuations.* American Geographical Society, New York. 51 p.

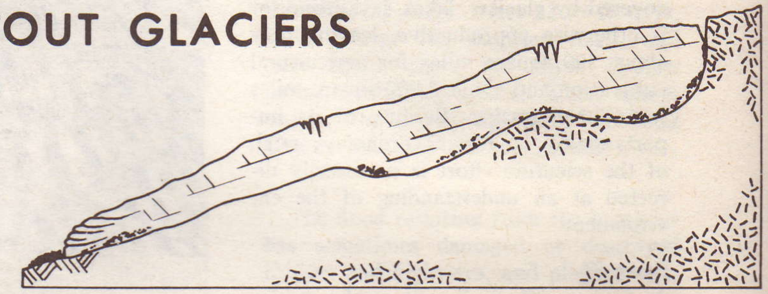
Sharp, Robert P. 1960. *Glaciers.* Condon Lectures, Oregon State System of Higher Education, Eugene, Oregon. 78 p.

Shumskii, P. A. 1964. *Principles of structural glaciology. The petrography of fresh-water ice as a method of glaciological investigation.* Translated by David Kraus. Dover Publications, Inc., New York. 497 p.

Wright, H. E., Jr., and Frey, David G. 1965. *The Quaternary of the United States.* Princeton University Press, Princeton, New Jersey. 922 p. ⚒

MATERIALS ABOUT GLACIERS





Especially for Teachers

Slides about glaciers and glaciation

There are several sources of 35mm slides on glaciers and glaciation. Among them are:

Ward's Natural Science Establishment, P.O. Box 1749, Monterey, California 93940 or P.O. Box 1712, Rochester, New York 14603. Catalog upon request (write on school or business letterhead). Ward's has a large selection of slides on alpine glaciation, continental glaciation, and glaciers of Alaska. Actual views of glaciers, as well as the erosive and depositional work of former glaciers of Europe are included. Price, each, for color slides is $1.00. Slides are of excellent quality.

Also available is a series of 30 black-and-white 35mm slides of the glaciers of Alaska, photographed by Bradford Washburn. Most are aerial photographs. Price, set of 30, $30.00; individual slides, $1.00 each.

Hubbard Scientific Company, P.O. Box 105, Northbrook, Illinois 60062. Catalog upon request (write on school or company letterhead). Hubbard has a large selection of teaching tools, including models, film loops, overhead transparencies, and slides, among others. Their 35mm slides are sold by sets, mounted in a plastic folder with explanatory captions. These groups are of use in the study of glaciation:

Glacial erosion and deposition. Set of 20, in color. Most deal with the relics of glaciation rather than the glaciers themselves. Price $15.00.

Landform features slides, correlating to book, *100 Topographic maps* (price $3.95). Slides show glacial topography in split-image; one half as it may be seen naturally; the other half with the particular feature outlined. These slides are photographs of topographic maps, not of the features themselves. Price, set of 20, $15.00.

Hubbard's geology view files, *Landform's I and II,* also includes slides of glacial features.

Films about glaciers

An annotated bibliography of 16mm films useful in college-level geology and earth science courses. By Noel Potter, Jr., Richard D. Bartels, and George R. Rapp, Jr. 1971. 50 p. Published as CEGS (Council on Education in the Geological Sciences) Programs Publication Number 9. Available on request from American Geological Institute, 2201 M Street, NW, Washington, D.C. 20037.

This publication lists films suitable for college-level teaching; fourteen films are included. Additional films are listed in:

An annotated bibliography of 16mm films useful in college-level geology and earth science courses: supplement. By George T. Ladd. 1973. 30 p. Published as CEGS (Council on Education in the Geological Sciences) Programs Publication Number 13. Available on request from American Geological Institute, 2201 M Street, NW, Washington, D.C. 20037.

Briefly reviewed are the following films:

- Archaeology in laboratories (Facsea)
- Avalanche control (U.S. Department of Agriculture)
- Evidence of the Ice Age (Cine-Pic)
- The face of the high Arctic (Encyclopaedia Britannica)
- Geological work of ice (Encyclopaedia Britannica)
- Glaciation (McGraw-Hill)
- Glacier on the move (Encyclopaedia Britannica)
- How do we know about the Ice Ages? (BFA)
- Legacies of the Ice Age (Indiana University)
- Mountain glaciers (Ohio State)
- Polar glaciology (U.S. Army)
- Rise and fall of the Great Lakes (McGraw-Hill)
- Snow (BFA)
- The story of two creeks (University of Wisconsin)
- What happens at the front of a glacier (University of British Columbia)
- White Cloud Peaks (Film Originals)
- White flood (CCM Films)

Film strips about glaciers and glaciation

Glaciers and the Ice Age. Encyclopaedia Britannica Educational Corporation, 925 North Michigan Avenue, Chicago, Illinois 60611 or 2494 Teagarden Street, San Leandro, California 94577. Available with disc or cassette. Approximately 44 strips in each set. Teacher's guide accompanies. Price, in color, discs, $11.00; cassettes, $12.95.

Work of snow and ice. Hubbard, 2855 Shermer Road, Northbrook, Illinois 60062. Forty-eight frames. Photos and text alternate. Price, $6.50.

Glaciers. Hubbard, 2855 Shermer Road, Northbrook, Illinois 60062. Price $7.00, with teacher's guide. Record available separately for $4.00; cassette, $6.00.

Film loops about glaciers

Glaciers, Part I, Alpine and valley glaciers. Shows glacial features, including ice falls, crevasses, and moraines.

Glaciers, Part II, Erosion and deposition. Shows effects of glaciation, including U-shaped valleys, cirques, glacial lakes, knife-edged ridges, waterfalls, and others.

Both parts are available in 8mm or super 8mm color, for $24.95 each. Hubbard, 2855 Shermer Road, Northbrook, Illinois 60062.

Study prints about glaciers and glaciation

Glaciers. A set of six 18"x13" mounted photographs with explanatory text. Set is sent in plastic envelope. *Glaciers* illustrates the types of glaciers and their characteristics. Ward's National Science Establishment, P.O. Box 1712, Rochester, New York 14603 or P.O. Box 1749, Monterey, California 93940. Price $7.95, color.

Overhead transparencies

Overlay ice sheet, showing how it was in glacial times, can be removed to show features resulting from glaciation (cirques, moraines, glaciated valleys, horn peaks). Hubbard, 2855 Shermer Road, Northbrook, Illinois 60062. Price, in heavy plastic for both transparencies, $3.95.

Alpine glaciation and continental glaciation, show glacial land forms. Removable overlays. Hubbard, 2855 Shermer Road, Northbrook, Illinois 60062. Price, $5.50 each. Study guide included. Grease pencil may be used on and removed from durable plastic overlays.

Work of glaciers, alpine and continental. Ward's National Science Establishment, P.O. Box 1712, Rochester, New York 14603 or P.O. Box 1749, Monterey, California 93940. Price, set of 11 transparencies, $44.00.

Set comes boxed; colored, clearly labeled diagrams for projection have accompanying text. A set of spirit masters for making duplicates (uncolored) of the slides for class use is included. Duplicate masters available. A very useful set.

Glacier and glaciation models

Alpine glacier model. Model in two parts: Heavy plastic overlay of mountain terrain with glacier; when removed, shows relief features of same terrain after glaciation. Size, 18"x24". Suitable for exhibit also. Complete with lesson plans. Available from Hubbard, 2855 Shermer Road, Northbrook, Illinois 60062 and from Ward's National Science Establishment, P.O. Box 1712, Rochester, New York 14603 or P.O. Box 1749, Monterey, California 93940. Price, $20.00.

Hubbard also has two geology land form series that includes glaciers. Correlated tapes available also.

Ward's has three series of geomorphological models that include glaciation. In addition, Ward's has a set of four Shaler-Davis models that deal with glaciation. Each model is made of plaster and is approximately 5"x7". Price for the glaciation set, $65.00.

Books on glaciers

Glaciers. By Robert P. Sharp. 1960. Condon Lectures, Oregon State System of Higher Education, Eugene, Oregon. 78 p. Price $1.25, paper. A plainly written, technical treatise on glaciers.

Glacier ice. By Austin Post and Edward R. LaChapelle. 1971. University of Washington Press, Seattle, Washington. 110 p. Price $20.00, cloth. Essentially a picture book (with superb aerial photographs), illustrating glaciers and glacial features. An accompanying text, tied directly to the photographs, makes this an unusually effective presentation. Highly recommended.

Many of the photographs in this article also appear in *Glacier ice.*

Glaciers and glacial erosion. Edited by Clifford Embleton. 1973. Available from Crane, Russak and Company, Inc., 52 Vanderbilt Avenue, New York, New York 10017. 287 p. Price $12.00.

A series of readings on glaciers, including some famous papers, such as "Glacial erosion in France, Switzerland, and Norway" by William Morris Davis; "The profile of maturity in Alpine glacial erosion", by Willard D. Johnson; "Crescentic gouges on glaciated surfaces", by G. K. Gilbert; and part of "Geologic history of Yosemite Valley", by Francois Matthes.

Encyclopedia of geomorphology. Edited by Rhodes W. Fairbridge. 1968. Published by Van Nostrand Reinhold Company, 450 West 33rd Street, New York, New York 10001. 1295 p. Price $38.50, hardbound.

Encyclopedia is just that; a collection of 410 articles on all manner of subjects in geomorphology. Like others in the encyclopedia series, this is an extremely useful book. All geological libraries should have it; most geologists will want it. But its use is not limited to geologists or geographers. Secondary teachers, engineers, planners—anyone interested in the earth and its use will need it as a ready reference tool. Besides its obvious use, the articles are interesting reading.

A considerable portion of the book is devoted to glaciation and glacial processes. It is an invaluable reference for teachers—or anyone—dealing with glacial phenomena.

Publications on glaciers

The U.S. Geological Survey has several useful illustrated pamphlets available on glaciers. Single copies are free on application to the U.S. Geological Survey, Washington, D.C. 20244.

Glaciers as a water resource. 1970. An illustrated pamphlet about glaciers.

The Great Ice Age. 1967. A booklet about the Pleistocene ice age and the marks left by glaciers.

Our changing continent. 1967. Several "ages" of the past are discussed briefly, including the Great Ice Age, the Age of Dinosaurs, and the Coal Age.

The breakout of Alaska's Lake George. 1969. How and when Lake George cuts through its dam of ice to empty itself into the Knik River and—eventually—the Gulf of Alaska.

These well-illustrated articles on glaciers, written especialy for hikers, should be of special interest to students:

"Climate changes and northwest glaciers". By Darryl Lloyd. *Off Belay,* January–February, 1972. No. 1. P. 10–13. Discusses the advances and retreats of the glaciers of the U.S. (outside Alaska) in the past two centuries.

"Glacier response". By Darryl Lloyd. *Off Belay,* April, 1972. No. 2. P. 7–11.